

‘Activated’ STAT proteins – a paradoxical consequence of inhibited JAK-STAT signalling in cytomegalovirus-infected cells

Running title: Cytomegaloviral inhibition of STAT3 signalling

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Abstract:

We have previously characterized mouse cytomegalovirus (MCMV)-encoded immune evasive interferon (IFN) signalling inhibition and identified the viral protein pM27 as inducer of proteasomal degradation of STAT2. Extending our analysis to STAT1 and STAT3, we found that MCMV infection neither destabilizes STAT1 protein nor prevents STAT1 tyrosine Y701 phosphorylation, nuclear translocation or the capability to bind GAS DNA-enhancer elements. Unexpectedly, the analysis of STAT3 revealed an induction of STAT3 Y705 phosphorylation by MCMV. In parallel, we found decreasing STAT3 protein amounts upon MCMV infection although STAT3 expression normally is positive autoregulative. STAT3 phosphorylation depended on the duration of MCMV infection, the infectious dose and MCMV gene expression but was independent of IFNAR1, IL-10, IL-6 and JAK2. Although STAT3 phosphorylation did not require MCMV *immediate early* (IE)1, pM27 and *late* gene expression, it was restricted to MCMV-infected cells and not transmitted to bystander cells. Despite intact STAT1 Y701 phosphorylation, IFN γ -induced target gene transcription (e.g. *IRF1* and *SOCS1*) was strongly impaired. Likewise, the induction of STAT3 target genes (e.g. *SOCS3*) by IL-6 was also abolished, indicating that MCMV antagonizes STAT1 and STAT3 despite the occurrence of tyrosine phosphorylation. Consistent with the lack of *SOCS1* induction, STAT1 phosphorylation was prolonged upon IFN γ treatment. We conclude that the inhibition of canonical STAT1 and STAT3 target gene expression abrogates their intrinsic negative feedback loops, leading to accumulation of phospho-Y-STAT3 and prolonged STAT1 phosphorylation. These findings challenge the generalization of Tyr-phosphorylated STATs necessarily being transcriptional active and document antagonistic effects of MCMV on STAT1/3-dependent target gene expression.

(250 words)

1 Introduction

2 Cytomegaloviruses (CMVs) are prototypical β -herpesviruses with an enveloped virion
3 coating a large double stranded DNA genome of ~230 kbp which encodes numerous viral
4 proteins. Upon infection, CMVs initiate a sequential and highly coordinated gene expression
5 profile, starting with *immediate early* (IE) transcripts, followed by *early* and *late* gene
6 products - the latter being simultaneously expressed with and depending on genome
7 amplification by rolling circle replication.

8 Although the infection in healthy individuals is mostly asymptomatic due to virus control by a
9 concerted response of the innate and adaptive immune system (1), primary as well as
10 recurrent CMV infections cause symptomatic or even fatal pathologies in immuno-
11 compromised or immature individuals. Irrespective of their robust immune stimulatory
12 capacity, CMVs circumvent sterile immunity and instead establish a lifelong latency.
13 Reactivation occurs upon immuno-suppressing and/or stressful conditions due to (re-)
14 initiation of the lytic viral replication program. Human CMV (HCMV, HHV-5, taxonomy ID:
15 10359) frequently causes congenital infections via a vertical transmission from the mother to
16 the developing foetus and constitutes the most frequent non-genetic congenital complication
17 in western countries (2).

18 CMVs have undergone an intimate and long lasting co-adaptation with their respective host
19 species and are thus highly species-specific, which restricts efficient viral replication to cells
20 of the native host species and thereby excludes experimentation with HCMV in animal
21 models. The related mouse cytomegalovirus [MCMV, Murid herpesvirus 1, taxonomy ID:
22 10366]) has a co-linear and partially homologous genome and infects mice (*Mus musculus*,
23 taxonomy ID: 10090) allowing to study cytomegaloviral pathogenesis. Additionally, MCMV
24 represents one of the few DNA viruses naturally infecting *Mus musculus* as its native host and
25 has therefore become a widely used model to explore virus-host interactions and to assess
26 their consequences *in vivo*.

27 Among the earliest immune responses raised against viruses is the secretion of interferons
28 (IFNs). IFNs are pleiotropic cytokines expressed upon encounter of pathogens or their
29 pathogen-associated molecular patterns (PAMPs). IFNs bind to specific cell surface resident
30 IFN receptors and subsequently induce a rapid janus kinase (JAK) mediated phosphorylation
31 of signal transducer and activator of transcription (STAT) which then instruct specific
32 transcriptional programs to (re-)enforce intrinsic resistance, induce innate immunity and
33 stimulate and recruit adaptive immune responses. Thereby, IFNs orchestrate the induction of
34 an antiviral state that efficiently restricts viral replication (3).

1 Type I IFNs (IFN α/β) mainly induce STAT1 and STAT2 Tyr (Y) phosphorylation (residues
2 Y701 and Y689, respectively) upon binding of the IFN to the heterodimeric IFNAR1-
3 IFNAR2 receptor complex and the accompanying activation of the receptor-associated
4 kinases JAK1 and tyrosine kinase 2 (Tyk2). STAT3 becomes also Y-phosphorylated (at
5 residue Y705) by type I IFNs. These STAT Y-phosphorylation events are essential for
6 transcriptional activation of STAT molecules (4-7) and are thus widely considered to
7 constitute a hallmark and faithful surrogate marker for STAT activation. Phosphorylated
8 STAT1 and STAT2 recruit IRF9 to form the IFN-stimulated gene factor 3 (ISGF3), which
9 binds to IFN-stimulated response elements (ISRE) to recruit the transcriptional machinery and
10 stimulate the expression of adjacent genes. In contrast, IFN γ mainly signals via Y-
11 phosphorylated STAT1 homodimers which are induced upon binding of IFN γ to the
12 heterodimeric IFNGR1-IFNGR2 receptor and the activation of JAK1 and JAK2.

13 Besides IFNs, STAT3 Y705 phosphorylation is also induced by a broad variety of growth
14 factors and cytokines (e.g. IL-6, IL-10, EGF, LIF, OSM and Leptin). It is noteworthy that
15 STAT3-activating stimuli play an important role in CMV biology. For example, *IL-6*
16 transcripts are strongly induced in HCMV-infected cells (8, 9) stimulating IL-6 secretion (10).
17 Interestingly, recent results document an important regulation of HCMV reactivation by IL-6
18 (11-13). Additionally, MCMV induces the expression of IL-10 to suppress MHC class II
19 presentation (14). HCMV encodes a STAT3-activating IL-10 homolog acquired by molecular
20 piracy (15).

21 Viruses counteract the antiviral activity of the IFN system by expressing IFN antagonists,
22 targeting e.g. JAK-STAT signal transduction (16, 17). We have identified and characterized
23 the MCMV-encoded IFN inhibitor pM27. Replication of a *M27* deletion virus mutant (Δ M27-
24 MCMV) is almost not affected in cell culture (18-21) but is highly attenuated *in vivo* (18, 21).
25 Using a forward genetic screening approach, we identified pM27 to be an IFN antagonist
26 targeting STAT2 (21) and thereby abrogating the induction of IFN target genes (21, 22).
27 Consistently, replication of Δ M27-MCMV is highly susceptible to IFNs in cell culture (21,
28 23). pM27 acts by recruiting cellular DDB1-containing ubiquitin ligase complexes and to
29 proteasomally degrade STAT2 (23). Like MCMV, HCMV also encodes a yet unknown
30 protein inducing proteasomal degradation of STAT2 (24).

31 Here, we extend our analysis to the interplay between MCMV and further STAT transcription
32 factors present in CMV target cells. Unexpectedly, we found prolonged STAT1 Y-
33 phosphorylation and seemingly autonomous STAT3 phosphorylation as consequence of viral
34 JAK-STAT inhibition instead of being a hallmark of STAT activation.

Material and Methods:

Cells and cytokines

NIH3T3 (ATCC CRL-1658), RAW 264.7 (ATCC TIB-71), M2-10B4 (kindly provided by Brendan Marshall [Medical College of Georgia, USA]), mHTC-K2 (25), STAT3^{flox/flox}, crisis immortalized IFNAR1- (26), respective C57BL/6 control fibroblasts, STAT3- (27), JAK2- (28), IL-6- and primary IL-10-deficient (prepared as described (29)) fibroblasts were grown in Dulbecco's modified eagle medium (D-MEM) with 10% (vol/vol) foetal bovine serum (Gibco [Invitrogen]), streptomycin, penicillin and 2 mM glutamine.

IFNs (mouse IFN α (#12100-1) and mouse IFN γ (#12500-1)) were purchased from PBL Biomedical Laboratories, New Jersey, USA. If not stated otherwise, cells were treated with 500 U/ml IFN. Hyper-IL-6 has been described previously (30).

Viruses, infection conditions and virus titration

Preparation, purification and titration of MCMV stocks was done as described previously (21, 26, 31). wt-MCMV and Δ M27-MCMV have been described previously (21). For the construction of Δ m157-MCMV:*mCherry*, a *frt*-site-flanked fragment encompassing the HCMV-derived major IE promoter/enhancer (MIEP) in front of the *mCherry* gene was introduced into a recombinant MCMV bacterial artificial chromosome (which already harbored a *frt* site instead of the *m157* CDS) by flp-mediated recombination. UV inactivation was conducted with indicated J/m² doses of UV irradiation in a CL-1000 UV cross-linker (UVP).

Electromobility shift assay (EMSA)

Extraction of fractionated EMSA lysates and the EMSA assay was performed as described (26). Briefly, cells were lysed in cytosolic extraction buffer (20 mM Hepes, pH 7.4, 10 mM KCl, 0.2% [vol/vol] NP-40, 0.1 mM EDTA, 10% [vol/vol] glycerol, 0.1 mM Na-vanadate, 0.1 mM PMSF, 1 mM dithiothreitol (DTT), Complete® protease inhibitors [Roche, Mannheim, Germany]). The extracts were centrifuged at 16,000 g for 16 s at 4°C, the supernatants were collected, centrifuged for 10 min and used as cytosolic extracts for EMSA. The pellets were washed in PBS and suspended in nuclear extraction buffer (20 mM HEPES, pH 7.6, 420 mM KCl, 0.1 mM vanadate, 20% [vol/vol] glycerol, 1 mM EDTA, 0.1 mM PMSF, 1 mM DTT, Complete® protease inhibitors [Roche, Mannheim, Germany]). After incubation on ice for 25 min the extracts were centrifuged at 16,000 g for 25 min at 4°C, and the supernatants were used as nuclear extracts. Both extracts were frozen immediately in liquid nitrogen until final

use. Nuclear or cytosolic lysates were incubated with 1 ng (~50 000 cpm) of (³²P)-labelled M67 GAS (32) probe for 20 min at room temperature. The DNA-protein complexes were separated on 4.7% (vol/vol) polyacrylamide, 22.5 mM TrisHCl, 22.5 mM borate and 50 μM EDTA gels, fixed and finally visualized by autoradiography. Supershifts were performed with a STAT1 antibody (Santa Cruz).

Immunoblotting

Cells were lysed in RIPA⁺-buffer (50 mM Tris-HCl, 150 mM NaCl, 1% [vol/vol] IGEPAL, 1% Na-Deoxycholate [weight/vol], 0.1% [weight/vol] SDS, 1 mM DTT, 0.2 mM phenylmethylsulfonyl fluoride (PMSF), 1 μg/ml leupeptin, 1 μg/ml pepstatin, 50 mM NaF, 0.1 mM Na-vanadate with Complete[®] protease inhibitors [Roche] pH 7.5). Samples were normalized according to Bradford protein staining and equal amounts were subjected to denaturing SDS-PAGE. Gels were blotted on nitrocellulose membranes (GE Healthcare) and probed with indicated antibodies. The same membrane was used and consecutively stripped with reblot solution (Millipore). The following antibodies were used: α-β-actin from Sigma-Aldrich; α-STAT3 (K-15), α-STAT3 (C-20), α-STAT3 (H-190), α-STAT3 (F-2), α-phospho-Y705 STAT3 (B-7), α-STAT1(E-23), α-IκBα (C-21), and α-IRF-1 (M-20) from Santa Cruz; α-phospho-Y701 STAT1, α-phospho-S727 STAT1, α-phospho-S727 STAT3 and α-Lamin A/C from Cell Signaling, α-SOCS3 (ab16030) from Abcam. α-pp89-IE1 (Croma101) and α-pM45 were provided by Stipan Jonjić, University of Rijeka, Croatia. The actual MCMV antigen of the α-pM45 was defined by co-immuno-precipitation and mass-spectrometry by Gabriela E. Androsiac, HHU Düsseldorf, Germany. Quantification of immunoblot signals was conducted using a Fusion FX7 (Vilber Lourmat).

Luciferase Assay

For reporter gene assays, a NIH3T3-derived cell line harbouring a GAS luciferase vector was selected. To do so, a fragment comprising the promoter/enhancer sequence and the fire fly (*Photinus pyralis*) luciferase gene from the pTA-GAS construct (Clontech) was sub-cloned into a pGene vector backbone conferring Zeocine resistance (Invitrogen). Cells were induced with 100 U/ml of the indicated recombinant mouse IFN. Luciferase activity was measured using the *luciferase reporter gene assay, high sensitivity* according to the manufacturer's instructions (Roche) using a microplate luminometer (model LB 96V; Berthold).

Northern blot analysis of specific transcripts

1 Total RNA was extracted from cells using the RNeasy Mini Kit (Qiagen). Total RNA was
2 subjected to MOPS gel electrophoresis and transferred to nylon membranes using the
3 TurboBlotter (Schleicher and Schuell). Probes were prepared by PCR with gene-specific
4 primers (Table 1) and digoxigenin-labelled dUTP (Roche) for detection of indicated
5 transcripts. Hybridization and detection were performed as described in Roche manuals.

6 7 *Analysis of nuclear translocation of STAT1*

8 For visualization of IFN- γ -induced nuclear translocation of STAT1, we constructed a STAT1-
9 EGFP fusion protein. Based on the expression vector pIRES2EGFP-mSTAT1HA (STAT1HA
10 amplified using primers mSTAT1-1 CGGCTAGCATGTCACAGTGGTTCGAGCTTC and
11 mSTAT1-HA2

12 CGCTCGAGTTAAGCGTAATCTGGAACATCGTATGGGTATACTGTGCTCATCATAC
13 TGTCAAATTC with total RNA of BALB/c MEF as template), we generated a PCR product
14 using the primers mSTAT1-1 and HA-EGFP-2
15 CGGAATTCGAGCGTAATCTGGAACATCGTATGGG. This fragment was digested with
16 *NheI* and *EcoRI* to clone it in two steps into pEGFP-N1, resulting in STAT1-EGFP. NIH3T3
17 fibroblasts were transfected (Superfect, Qiagen) with a STAT1-EGFP expression vector. 24 h
18 post transfection, cells were mock-treated or infected with Δ m157-MCMV:*mCherry* (2
19 PFU/cell). 16 h post infection, cells were incubated with 200 U/ml IFN- γ for 45 min. After
20 IFN-treatment, cells were fixed using 4% (weight/vol) paraformaldehyde-PBS for 20 min.
21 IFN γ -induced nuclear translocation of STAT1-EGFP was visualized by fluorescence
22 microscopy using a Leica DM IL LED Fluo and LAS V4.0.

23 24 *Chromatin immuno-precipitation (ChIP)*

25 Crosslinking was achieved by adding formaldehyde (1% [vol/vol] final concentration) to
26 cells. After 10 min, crosslinking was stopped by addition of glycine (125 mM final
27 concentration). Cells were washed twice with ice cold PBS and subsequently detached from
28 the cell culture plates by scraping in ice cold Na-butyrate containing PBS. Cells were washed
29 in buffer 1 (0.5% [vol/vol] Triton-X-100, 20 mM EDTA, 0.5 mM EGTA, 20 mM HEPES pH
30 7.5 and 20 mM Na-butyrate) and buffer 2 (400 mM NaCl, 2 mM EDTA, 0.5 mM EGTA, 20
31 mM HEPES pH 7.5 and 20 mM Na-butyrate). Cells were lysed in lysis buffer (150 mM NaCl,
32 25 mM Tris pH 7.5, 5 mM EDTA, 1% [vol/vol] Triton-X-100, 0.1% [weight/vol] SDS, 0.5%
33 [weight/vol] Na-deoxycholate, 1 mM PMSF, 10 mM Na-butyrate and Complete protease
34 inhibitors (Roche). Lysates were sonicated (5 cycles [2 min each]; amplitude 30; cycle 0.5 on

ice in a Sartorius Labsonic P) and subsequently cleared by centrifugation. Supernatants were pre-cleared by addition of protein G sepharose (PGS) in presence of 100 µg/l salmon sperm DNA and 500 µg/l BSA. After the pre-clearing procedure, an aliquot was stored ('input'). Precipitation was performed over night at 4°C using a STAT1-specific antibody (E-23; Santa Cruz). Immune complexes were precipitated using PGS (1-2 h at 4°C). Afterwards, the sepharose was washed twice with RIPA buffer (150 mM NaCl, 50 mM Tris pH 8.0, 0.1% [weight/vol] SDS, 0.5% Na-deoxycholate and 1% [vol/vol] NP-40), twice with high salt buffer (500 mM NaCl, 50 mM Tris pH 8.0, 0.1% [weight/vol] SDS and 1% [vol/vol] NP-40), twice with LiCl buffer (25 mM LiCl, 50 mM Tris pH 8.0, 0.5% [weight/vol] Na-deoxycholate and 1% [vol/vol] NP-40) and twice with TE buffer (10 mM Tris pH 8.0 and 1 mM EDTA). Immune complexes were eluted using elution buffer (2% [weight/vol] SDS, 0.1 M NaHCO₃ and 10 mM DTT). Crosslinking was reversed by addition of 0.05 volume of 4 M NaCl and subsequent incubation for 4 h at 65°C. Proteins were digested using Proteinase K. After standard phenol/chloroform extraction, ethanol precipitation and washing with 70% (vol/vol) ethanol, immune-precipitated DNA was analysed by PCR using previously described primers (33) specific for the mouse *irf-1* promoter (5'- AGCACAGCTGCCTTGTACTTCC-3' and 5'- CTTAGACTGTGAAAGCACGTCC-3') yielding a 229 nucleotide long product.

Results:

MCMV abrogates STAT1 signalling downstream of intact STAT1 Y701 phosphorylation, nuclear translocation and DNA-binding

Intrigued by the central role of STAT1 for type I and type II IFN signalling, we investigated the interplay between MCMV and STAT-activation by IFNs. In clear contrast to STAT2, which is rapidly degraded upon MCMV infection (21, 23), STAT1 protein amounts remained stable in MCMV-infected cells (Fig. 1A). STAT1 Y701 phosphorylation was virtually absent in untreated cells but became strongly induced upon exposure to IFN γ (Fig. 1A). A comparable IFN γ -induced STAT1 phosphorylation was also evident in MCMV-infected cells (Fig. 1A) indicating that IFNGR proximal events of JAK-STAT1 signalling are not affected by MCMV-encoded IFN antagonists. Nuclear translocation of STAT1 was also not inhibited by MCMV since equal amounts of phosphorylated STAT1 were detected in nuclear lysates of IFN γ -incubated MCMV-infected cells and mock control cells (Fig. 1A, right panel). Consistently, the nuclear translocation of transiently transfected GFP-tagged STAT1 was not compromised upon MCMV infection (Fig. 1B). The analysis of the DNA-binding capacity of STAT1 by electro-mobility shift assay (EMSA) revealed that STAT1:STAT1 homodimers retained their capacity to bind to gamma activated sequence (GAS) DNA elements after MCMV infection - irrespective of *M27* coding capacity (Fig. 1C). Chromatin immunoprecipitation (ChIP) experiments confirmed the intact ability of STAT1 to bind to endogenous GAS DNA elements (here the *irf-1* promoter) in MCMV-infected cells upon IFN γ exposure (Fig. 1D). To test the ability of MCMV to antagonize GAS-dependent gene expression, we constructed a stable MCMV-permissive NIH3T3 cell line harbouring the firefly (*Photinus pyralis*) luciferase reporter gene under the control of a minimal promoter and a GAS enhancer element. In mock-infected cells, IFN γ strongly induced luciferase activity, but the response was significantly inhibited upon MCMV infection - again irrespective of *M27* coding capacity (Fig. 1E). To rule out that this effect is influenced by previously observed effects of CMV infections on gene expression derived from reporter plasmids (34), we studied the ability of MCMV to counteract the IFN γ -dependent induction of endogenous *IRF-1* mRNA by northern blotting. 4 h of MCMV infection already sufficed to antagonize IFN γ -induced *IRF-1* transcription (Fig. 1F). These results demonstrate that MCMV abrogates IFN γ -induced gene expression without compromising overall STAT1 protein amounts, receptor-proximal Y701 STAT1 phosphorylation, nuclear translocation of STAT1 or the capability to bind to DNA - largely confirming previous reports (35). Additionally, our results reveal that this inhibition is not influenced by pM27, documenting

1 the existence of at least one additional MCMV-encoded antagonist of JAK-STAT signal
2 transduction.

3 4 *MCMV gene expression induces IFNAR1-independent STAT3 phosphorylation*

5 Given that STAT1 and STAT3 are highly homologous proteins (53% identical and 72%
6 similar) and that STAT3 transduces signals of pro- as well as anti-inflammatory cytokines
7 that play a crucial role in CMV immune control and pathogenesis (11-14), we extended our
8 analysis to STAT3. In contrast to STAT1, a basal STAT3 Y705 phosphorylation was
9 frequently (depending on exposure time of the films) observed in untreated, mock-infected
10 cells. Nevertheless, we observed a substantial increase of STAT3 Y705 phosphorylation upon
11 MCMV infection (Fig. 2A-C). Surprisingly, global STAT3 protein amounts simultaneously
12 declined in MCMV-infected cells as revealed by two different STAT3-specific antibodies
13 recognizing different parts of STAT3 (Fig. 2A-C). Y705 phosphorylation by MCMV was
14 invariably evident in a variety of cells including NIH3T3, M2-10B4, mHTC-K2 and others
15 (see Fig. 2A-F and data not shown). The extent of the virus-induced Y705 phosphorylation
16 was comparable to the effect elicited by treatment with 20 ng/ml Hyper-IL-6 - a STAT3-
17 activating designer cytokine generated by fusion of the coding sequence of IL-6 to the
18 extracellular domain of the gp80 subunit of the IL-6 receptor. Conversely, the MCMV-
19 induced decline in overall STAT3 amounts was not observed in Hyper-IL-6 treated cells
20 suggesting that the phosphorylation event does not preclude STAT3 recognition by the used
21 antibodies (C-20 and K-15). To confirm the detected protein band to represent truly STAT3,
22 we performed an experiment in STAT3-deficient cells. We observed STAT3 phosphorylation
23 upon MCMV infection in STAT3-positive cells, but no signal was detectable in STAT3-
24 deficient cells (Fig. 2B). Since the respective membranes were probed in a sequential manner,
25 STAT3 was also detected on separate membranes by different antibodies in parallel to ensure
26 that such procedure does not mask secondary STAT3 detection. We reproduced increased
27 levels of Y705 phosphorylation despite an overall reduction of STAT3 protein amounts in
28 MCMV-infected cells (Fig. 2C). The decrease of STAT3 and the parallel increase of
29 phosphorylated STAT3 was quantified (Fig. 2D). An increasing MCMV infection dose was
30 directly positively correlated with STAT3 Y705 phosphorylation as well as reduction of the
31 overall STAT3 protein amount (Fig. 2E).

32 Among other cytokines and growth factors, IFN α is known to induce STAT3 phosphorylation
33 (36). This effect was also observed in MCMV-permissive NIH3T3 cells (Fig. 2F). Since
34 MCMV infection initially induces type I IFN production (31), we used IFNAR1-deficient

1 cells to test if the observed STAT3 phosphorylation is caused by type I IFN. STAT3
2 phosphorylation and reduction of STAT3 protein amounts were observed with almost
3 congruent kinetics in IFNAR1-deficient and identically immortalized C57BL/6 fibroblasts
4 (Fig. 2G), indicating that both effects on STAT3 are IFNAR1-independent.

5 To analyse if viral gene expression is required for STAT3 modulation, NIH3T3 cells were
6 infected with MCMV virions which had been inactivated with grading UV doses (250 -
7 10,000 J/m²). Subsequently, STAT3 phosphorylation and global STAT3 protein amounts
8 were assessed by immunoblot. UV-inactivation of viral gene expression, as documented by
9 pp89-IE1 detection, abrogated STAT3 phosphorylation and reduction (Fig. 2H), indicating
10 that cytomegaloviral gene expression is essential for the observed modulation of STAT3.

11 We also detected STAT3 phosphorylation upon reversible application of protein synthesis
12 inhibitor Cycloheximide (CHX) followed by Actinomycin D (ActD) inhibition of
13 transcription leading to MCMV gene expression restricted to *immediate early* (IE) gene
14 products (37). However, this result cannot be interpreted as a proof for the responsibility of
15 viral *IE* genes due to similar drug-induced changes in STAT3 phosphorylation levels in UV-
16 MCMV as well as mock-infected cells (data not shown). A previously described fibroblast
17 cell line stably transfected with the *IE* gene region encompassing the respective *HindIII*
18 fragment of MCMV and thus being able to complement the growth of MCMV mutants
19 lacking the essential gene *ie3* (38), did not exhibit overt STAT3 phosphorylation or reduced
20 STAT3 protein amounts in comparison to parental NIH3T3 cells (data not shown), suggesting
21 that *ie* gene expression is not sufficient for the observed changes of STAT3.

22 To evaluate whether MCMV *late* gene expression is required for the effects on STAT3, we
23 infected cells in the presence of ganciclovir (GCV) - a drug which interferes with MCMV
24 DNA replication and thereby strongly reduces the accompanying viral *late* gene expression.
25 *Late* gene expression was neither essential for the phosphorylation of STAT3 nor for the
26 reduction of STAT3 overall amounts (Fig. 2I). Taken together, these results reveal that (a)
27 MCMV *IE*- and/or *early*-expressed gene product(s) induce(s) a sustained STAT3
28 phosphorylation and simultaneously reduce(s) STAT3 overall amounts.

29
30 *The MCMV-induced STAT3 Y705 phosphorylation occurs independent of IL-6, IL-10, gp130*
31 *and JAK2 and is restricted to infected cells*

32 As mentioned above, MCMV induces cytokines like IL-6 and IL-10, which mainly signal via
33 STAT3. Therefore, we tested if these cytokines are involved in the MCMV-induced STAT3
34 Y705 phosphorylation. Fibroblasts deficient for IL-6 and IL-10, respectively, both exhibited

1 STAT3 phosphorylation upon MCMV infection (Fig. 3A), indicating that these interleukins
2 are not essential for the observed phosphorylation. Since JAK2 is known to be crucial for the
3 signalling of a variety of cytokine receptors (28, 39), we assessed JAK2-deficient fibroblasts,
4 but again we observed STAT3 phosphorylation upon MCMV infection (Fig. 3A). However,
5 we could not exclude the possibility that STAT3 phosphorylation results from redundant
6 signalling via several receptors. Paralleling STAT3 phosphorylation, the reduction of the
7 overall STAT3 protein amount was also evident in the three gene-deficient cells and the
8 control fibroblasts (Fig. 3A).

9 STAT3 can be phosphorylated by cytokines via receptor bound janus kinases but also by
10 growth factors via receptor tyrosine kinases (RTKs) and by cytoplasmic kinases like c-Src
11 (40) and BCR-ABL (41, 42). Several STAT3-activating cytokines signal via a heterodimeric
12 receptor complex composed of a cytokine-specific subunit and the gp130 signalling module.
13 Soluble gp130-Fc blocks gp130-dependent IL-6 signalling and to a lesser extent LIF and
14 OSM signalling (43). Therefore, we used commercially available soluble gp130-Fc, to test the
15 involvement of gp130 in MCMV-induced STAT3 phosphorylation. As expected, soluble
16 gp130 blocked Hyper-IL-6-dependent STAT3 activation, but the STAT3 phosphorylation by
17 MCMV was not impaired (data not shown).

18 Next, we transferred conditioned medium (sterile-filtered or UV-inactivated) from MCMV-
19 infected NIH3T3 cells (which exhibited substantial STAT3 phosphorylation) to uninfected
20 fibroblasts and RAW 264.7 macrophages, respectively. Conditioned medium did not induce
21 STAT3 phosphorylation above background in fibroblasts or RAW cells (Fig. 3B).
22 Subsequently, we conducted transwell experiments in which MCMV-infected and uninfected
23 cells continuously share the same medium. Again, STAT3 phosphorylation was only
24 observed in infected cells but not in uninfected bystander cells (Fig. 3C), suggesting that the
25 STAT3 Y705 phosphorylating principle is restricted to infected cells and not transferable to
26 neighbouring cells when MCMV transmission is prevented. From these data we assume that
27 STAT3 phosphorylation does not require a secreted factor released from infected cells,
28 although we cannot formally rule out the implication of membrane bound cytokines (like for
29 example the tumour necrosis factor (TNF) superfamily member LIGHT which has been
30 shown to induce STAT3 phosphorylation (44)).

31 Under standard (non-serum-starved) culture conditions, cells are constantly exposed to
32 growth factors present in the foetal bovine serum contained in the cell-culture media. Several
33 growth factors (e.g. basic fibroblast growth factor (45) and insulin-like growth factor I (46))
34 have been demonstrated to induce STAT3 phosphorylation. We therefore tested if and how

1 such growth factors influence the MCMV-induced STAT3 phosphorylation. Even though
2 STAT3 phosphorylation was restricted to cells being MCMV-infected and was not
3 transmitted to bystander cells (see above), we found that increasing foetal bovine serum
4 (FBS) present in the cell culture medium concentration-dependently enhanced STAT3
5 phosphorylation in MCMV-infected cells (Fig. 3D - for a discussion of this finding see
6 below).

7 Taken together, MCMV induces STAT3 phosphorylation in infected cells by an IFNAR1-,
8 IL-6-, IL-10-, gp130- and JAK2-independent principle which is restricted to infected cells. In
9 addition, growth factors present in the cell culture media (e.g. FBS) have the potency to
10 further enhance STAT3 phosphorylation in MCMV-infected cells.

11 *MCMV interferes with STAT1 and STAT3-dependent gene expression*

12 Based on our finding that tyrosine phosphorylated STAT1 molecules are transcriptionally
13 inert in MCMV-infected cells (Fig. 1), we raised the question if MCMV-induced Y705
14 phosphorylated STAT3 is actually active in terms of target gene expression. To this end we
15 chose the canonical target gene SOCS3 encoding an immediately responsive and highly
16 sensitive surrogate marker protein of STAT3 function. Cells were infected with MCMV and
17 24 h post infection treated with Hyper-IL-6 and IFN γ , respectively. Interestingly, despite
18 efficient induction of Y705 phosphorylated STAT3 in MCMV-infected cells, we did not
19 observe the expected increase of SOCS3 amounts. On top of that, an additional stimulation
20 with Hyper-IL-6 or IFN γ , which strongly induces SOCS3 in mock cells, failed to induce
21 SOCS3 in MCMV-infected cells (Fig. 4A). Adequate MCMV infection was documented by
22 detection of pp89-IE1 and equal protein loading by detection of β -actin. As expected, MCMV
23 infection resulted in reduced STAT3 protein amounts (Fig. 4A).

24 To test if the blockade of the SOCS3 response is specific or part of a general inhibition and
25 whether it is executed on transcriptional level or acts post-transcriptionally, we performed
26 northern blot experiments. We found that MCMV infection drastically inhibited the induction
27 of *SOCS3*, *SOCS1*, *IRF-1* and *cEBP δ* transcripts by IFN γ and the induction of multiple
28 STAT3 target genes including *SOCS3*, *IRF-1*, *cEBP δ* , *JunB* and *c-Myc* by Hyper-IL-6 (Fig.
29 4B).

30 In this context, it is noteworthy that it is well documented that an auto-regulative STAT3
31 circuit exists since STAT3 gene transcription is STAT3-dependent (47-49). Thus, the decline
32 of STAT3 protein amount might represent a consequence of the cytomegaloviral disruption of
33 canonical STAT3-dependent signal transduction and gene expression. Therefore, we tested
34

1 the expression of *STAT3* mRNA and found it to be significantly reduced upon MCMV
2 infection (Fig. 4B). In summary, MCMV interferes with STAT1 and STAT3 signal
3 transduction, leading to impaired target gene induction.

4 To reach the maximal rate of transcriptional activity, certain STAT molecules (including
5 STAT1 and STAT3) require additional phosphorylation of serine residue 727 (50). Since our
6 data uncover a MCMV-encoded inhibition of STAT1 and STAT3 target gene expression at a
7 step beyond tyrosine phosphorylation, we assessed Ser727 phosphorylation of STAT1 and
8 STAT3 in MCMV-infected cells upon treatment with IFN γ or Hyper-IL-6. We found that the
9 IFN γ -induced Ser727 phosphorylation was not inhibited by MCMV (Fig. 5). MCMV
10 infection did also not significantly change the level of constitutive Ser727 STAT3
11 phosphorylation in unconditioned cells (Fig. 5). Nevertheless, the Hyper-IL-6-induced
12 increase in Ser727 phosphorylation of STAT3 was to a certain extent reduced in MCMV-
13 infected cells (irrespective of *M27* coding capacity) compared to mock-infected cells or cells
14 infected with UV-irradiated MCMV (Fig. 5). We interpret this minor change in Ser727
15 phosphorylated STAT3 in MCMV-infected cells as indirect consequence of the reduced
16 overall STAT3 amounts.

18 *MCMV infection prolongs IFN γ -induced STAT1 Y701 phosphorylation*

19 JAK-STAT signalling pathways are highly auto-regulative. Upon activation, negative feed-
20 back regulation is initiated by *de novo* expression of proteins like SOCS1, SOCS3, PIAS or
21 Usp18 which terminate the signalling process. Having demonstrated that MCMV infection
22 antagonizes SOCS1 and SOCS3 induction upon IFN γ and Hyper-IL-6 stimulation, we raised
23 the question whether the MCMV-encoded inhibitor, which acts on the level of transcriptional
24 activation after effected phosphorylation, would prevent the expression of negative feed-back
25 regulators and thereby counterintuitively prolong IFN γ -induced STAT1 phosphorylation. To
26 test this hypothesis, we pulse stimulated infected or non-infected cells for a short period (30
27 min) with IFN γ . Afterwards, we vigorously washed the cells to remove the IFN γ and then
28 followed the slope of declining STAT1 phosphorylation levels over a period of 8 h. As shown
29 in Fig. 6, STAT1 phosphorylation was virtually undetectable in untreated cells but readily
30 observed after adding IFN γ . In mock infected cells, STAT1 phosphorylation declined within 4
31 h. Conversely, in MCMV-infected cells a substantial amount of phosphorylated STAT1 was
32 still apparent after 8 h. *M27* coding capacity did not affect this prolongation of STAT1
33 phosphorylation. We concluded that MCMV interferes with IFN γ -induced gene expression on
34 the transcriptional level downstream of STAT1 Y701 phosphorylation resulting in abrogation

1 of the induction of the negative feedback loop (e.g. SOCS1 expression) leading to prolonged
2 STAT1 phosphorylation upon incubation with IFN γ .

4 *Neither pIE1pp89 nor pM27 are essential for the cytomegaloviral STAT3 regulation*

5 HCMV IE1-pp72 has been described as inhibitor of IFN-JAK-STAT signalling which
6 antagonizes ISRE signal transduction and simultaneously induces GAF-like responses (51,
7 52). Despite the limited primary sequence conservation between HCMV IE1-pp72 and
8 MCMV IE1-pp89 (~22% identity and ~42% similarity within a ~190 amino acid stretch
9 [residues 23-197 in HCMV IE1-pp72 and 33-210 in MCMV pp89-IE1, respectively]), the
10 MCMV homolog IE1-pp89 was found to co-precipitate with human STAT2 (53) defining
11 MCMV-pIE1 as potential candidate for a STAT-specific IFN antagonist. Therefore, we tested
12 if the STAT3 phosphorylation, reduction of the overall STAT3 amount and the inhibition of
13 target gene expression are preserved in cells infected with an MCMV mutant lacking the *ie1*
14 coding capacity. All three effects were found to be independent of *ie1* (Fig. 7A).

15 Besides pIE1-pp72, the only other known cytomegaloviral antagonist of JAK-STAT signal
16 transduction is pM27 (54). Consequently, we tested if *M27* is required for STAT3
17 modulation. But Δ M27-MCMV was also fully capable to stimulate STAT3 phosphorylation,
18 reduced overall STAT3 amounts and antagonized SOCS3 expression (Fig. 7B). These results
19 rule out an essential contribution of *M27* to the herein described regulation of STAT3 signal
20 transduction and the accompanying inhibition of target gene induction.

22 *MCMV reveals a dynamic equilibrium of STAT3 activation and deactivation*

23 MCMV interferes with STAT1- and STAT3-dependent gene expression in a strikingly similar
24 manner. In both cases, the expression of target genes is antagonized on the transcriptional
25 level despite the nuclear presence of Tyr-phosphorylated STATs. The lack of target gene
26 expression includes the well-known negative feedback regulators SOCS1 and SOCS3,
27 explaining the exaggerated tyrosine phosphorylation. Nevertheless, STAT1 phosphorylation
28 is prolonged but requires the external stimulus IFN γ , whereas STAT3 phosphorylation is
29 seemingly 'autonomous'. How can this apparent difference be reconciled? We hypothesize
30 that cell culture media including FBS contains stimuli like growth factors which induce low-
31 level of 'constitutive' STAT3 Y705 phosphorylation. These growth factors induce STAT3
32 phosphorylation which stimulates gene expression including the STAT3-dependent mediators
33 of the negative feedback (e.g. SOCS3) constantly balancing phosphorylated STAT3 at low
34 level. Consistently, cre-recombinase induced SOCS3 excision has been found to lead to

1 increased levels of tyrosine-activated STAT3 (55). To test if such a low level STAT3
2 activation exists in MCMV-permissive cells, we used the broad spectrum phosphatase
3 inhibitor sodium vanadate to interfere with STAT3 de-phosphorylation. A 15 min treatment
4 leading to a blockade of cellular phosphatases already induced accumulation of
5 phosphorylated STAT3 eventually resulting in SOCS3 protein induction (Fig. 8A). This
6 finding indicates that a fine-tuned dynamic equilibrium of STAT3 phosphorylation, gene
7 expression of negative feed-back regulators and subsequent dephosphorylation of STAT3
8 exists in MCMV-permissive cells and that uncoupling of activation and subsequent negative
9 feed-back inhibition results in accumulating phospho-STAT3. We made further use of this
10 sodium-vanadate-mediated uncoupling to induce a long-term ‘tyrosine phosphorylation state’
11 and the accompanied SOCS3 induction in cells. Consistent with general inhibition of STAT3
12 target gene expression, MCMV-infection also precluded SOCS3 and IRF-1 protein expression
13 upon long-term sodium-vanadate incubation (Fig. 8B).
14 Taken together, the herein described MCMV-encoded STAT3 inhibition reveals the existence
15 of a dynamic equilibrium of STAT3 by uncoupling phosphorylation and induction of
16 mediators of the negative feed-back loop.

Discussion:

We found that MCMV induces seemingly cytokine-autonomous STAT3 phosphorylation. STAT3 phosphorylation is essential for STAT3 activation and thus considered to constitute a faithful surrogate marker for transcriptional STAT3 activity. Although STAT3 is known to stimulate its own transcription (47-49), STAT3 phosphorylation in MCMV-infected cells was accompanied by a reduction of overall STAT3 amounts. This contradiction led to the finding that even a strong external stimulation like Hyper-IL-6 failed to induce all tested STAT3 target genes in MCMV-infected cells, documenting the existence of a potent MCMV-encoded antagonist of STAT3 signal transduction. A comprehensive molecular analysis revealed that MCMV interferes with STAT1- and STAT3-dependent signalling after effected tyrosine phosphorylation, thereby also compromising the intrinsic negative feedback loop otherwise executed by proteins like SOCS1 and SOCS3. Due to the lack of these negative regulators, the dynamic equilibrium of STAT phosphorylation and subsequent inactivation is uncoupled upon MCMV infection, leading to the accumulation of transcriptional inactive phospho-STAT3. The on-rate of the intrinsic equilibrium is influenced by growth factors present in the cell culture medium and especially the FBS. Therefore, increasing FBS concentrations dose-dependently increase STAT3 phosphorylation in MCMV-infected cells.

In contrast to STAT3, which is activated by a broad variety of cytokines, interleukins and growth factors, only very few cytokines e.g. IFNs and IL-35 (56) critically rely on STAT1. Therefore, STAT1 phosphorylation is not induced by constituents of serum and untreated cells virtually do not phosphorylate STAT1 and therefore no accumulation can be observed upon MCMV infection alone. Nevertheless, once the cell encounters STAT1-activating cytokines like IFN γ , STAT1 phosphorylation is also prolonged in MCMV-infected cells, yet it remains transcriptionally inert.

STAT tyrosine phosphorylation - a true hallmark for transcriptional activity?

Under normal conditions, phosphorylation of STAT1 and STAT3 at Y701 and Y705, respectively, is undoubtedly crucial for STAT activation. Since highly specific antibodies are available, the determination of the phosphorylation status represents a widely applied way to assess activity of STATs. Our data uncover a biological condition (i.e. virus infection) which challenges the view that tyrosine phosphorylated STATs are necessarily transcriptional active. This example of stalled STAT transcription complexes demonstrates the necessity to conduct further experiments to unequivocally prove the transcriptional activity of tyrosine phosphorylated STAT molecule species. Textbook schemes usually simplify JAK-STAT

1 signal transduction by only depicting STAT factors binding to respective DNA enhancer
2 elements directly resulting in target gene expression. Apparently, the process of
3 transcriptional initiation and transcription by STATs is a highly regulated process requiring
4 precisely choreographed activity of multiple proteins like co-activators, the mediator complex
5 and the RNA polymerase II complex (see for example (57, 58)). Our data indicate that
6 MCMV interferes with at least one factor involved in this step of regulation.

7 8 *Implications for $\Delta M27$ -MCMV pathogenesis*

9 We have previously described the MCMV-encoded protein pM27 as potent STAT2-specific
10 IFN antagonist (21-24) which interferes with type I IFN signal transduction by inducing rapid
11 proteasomal degradation of STAT2 via recruiting STAT2 to DDB1-containing ubiquitin
12 ligase complexes (23). In absence of *M27*, MCMV hardly interferes with IFN α -dependent
13 gene expression (21), strongly suggesting that pM27 is essential and sufficient to antagonize
14 formation of functional ISGF3 (STAT2:STAT1:IRF9) complexes. Here, we have
15 characterized a second *M27*-independent MCMV-encoded antagonism targeting both STAT1
16 and STAT3 signalling. Together both inhibitors preclude type I and type II IFN responses.

17 The presence of IFN α -dependent gene expression observed in $\Delta M27$ -MCMV-infected cells
18 together with the pronounced IFN susceptibility of $\Delta M27$ -MCMV *in vitro* and *in vivo* (21-23)
19 indicate that the herein described second MCMV-encoded IFN antagonist does not (or only to
20 a limited degree) affects ISGF3 complexes and that both MCMV-encoded inhibitors possess
21 non-redundant functions.

22 $\Delta M27$ -MCMV replication is over-proportionally susceptible to IFN α , but replication is
23 almost completely abrogated in IFN γ -conditioned cells (21). This might be in part explained
24 by IFN γ -dependent STAT2 phosphorylation (21, 59, 60) but IFN γ -induced Y689 STAT2
25 phosphorylation is less pronounced compared to stimulation by type I IFNs, yet the antiviral
26 effect of IFN γ is more potent (21). Our data reveal that phosphorylated STAT3 and STAT1
27 (in presence of IFN γ) accumulate in MCMV-infected cells but remain transcriptionally inert.
28 In the wt-MCMV infection scenario, STAT2-dependent gene expression is abrogated by
29 pM27-dependent STAT2 degradation. Upon $\Delta M27$ -MCMV infection, increased and
30 prolonged tyrosine phosphorylation of STAT3 and STAT1, respectively, join STAT2 which
31 seems to bypass the second inhibitor of STAT1 signalling. Together these STATs induce an
32 'overshooting' antiviral state via trans-signalling from IFN γ to ISRE-driven ISGs.

33 34 *MCMV effects on ISGF3 vs. GAF*

1 As outlined above, the biological phenotype of Δ M27-MCMV and the results of our
2 molecular analysis of the JAK-STAT signalling events in MCMV-infected cells indicate that
3 ISGF3 complexes are rather resistant against the herein described cytomegaloviral inhibitor,
4 whereas STAT1 and STAT3 homodimers are sensitive. Such a differential inhibition can only
5 be explained if we infer that the (co-) transcription factor complexes (e.g. p300, CBP, the
6 mediator complex and others) recruited by ISGF3 significantly differ from the complexes
7 utilized by STAT1 and/or STAT3 homodimers.

8 STAT1 is absolutely essential for the generation of functional ISGF3 complexes and thus type
9 I IFNs fail to induce gene expression in STAT1-deficient cells. Nevertheless, a full length
10 transactivation domain (TAD) of STAT1 seems not to be required for ISGF3 signalling: The
11 short splice isoform of STAT1 (STAT1 β) lacks large parts of the C-terminal STAT1 TAD
12 and is insufficient to generate transcriptionally active STAT1 homodimers. However,
13 functional ISGF3 complexes can be formed by this STAT1 β splice isoform (61). Thus, the
14 transcriptional activation of ISGF3 relies on the TAD of STAT2 whereas the transcriptional
15 activation of STAT1 homodimers depends on the TAD of STAT1. Consistently, specific co-
16 regulatory proteins have been described. For example, *N-myc and STAT interactor* (Nmi)
17 potentiates STAT-dependent gene expression. Interestingly, Nmi binds all STATs except
18 STAT2 (62). Additionally, ISGF3 signalling has been shown to require an interaction with the
19 mediator complex. In this context, STAT2 physically interacts with the mediator components
20 DRIP77 and DRIP150, but none of the tested mediator complex components co-precipitates
21 with STAT1 or STAT3 (57).

22 We infer that the suspected cytomegaloviral inhibitor of JAK-STAT signalling targets a
23 specific (co-) transactivator involved in STAT1 and STAT3 signalling, which is dispensable
24 (or redundant) in terms of ISGF3 signal transduction.

26 *Potential biological implications for the viral inhibition of STAT3 signalling*

27 Given the wealth of knowledge concerning IFN-induced effector mechanisms directly or
28 indirectly interfering with viral replication, the existence of viral antagonists targeting STAT1
29 can easily be understood (54). Less obvious is the ‘rationale’ behind the herewith described
30 viral modulation of STAT3 signal transduction, especially because several viruses (e.g. Rous
31 Sarcoma Virus, Hepatitis C Virus, Herpesvirus Saimiri, Epstein-Barr Virus and Kaposi’s
32 Sarcoma-associated Herpesvirus) encode proteins which induce genuine STAT3 activation
33 (63-67). Nevertheless, other viruses besides MCMV also inactivate STAT3, e.g. mumps virus
34 induces proteasomal degradation of STAT3 (68). This divergence might be based on

1 differences in the viral life styles and authentic STAT3 activation may be correlated with cell
2 transforming potential.

3 A simple explanation for STAT3 inactivation would be that MCMV targets STAT1 and that
4 STAT3 inhibition represents merely a ‘collateral damage’ resulting from overlapping
5 transcriptional co-activators used by both STATs. We favour the interpretation that STAT3
6 modulation constitutes a selective advantage for MCMV on its own. Recently, it was shown
7 that IL-6 induces PML expression via STAT3 (69). PML is well known to restrict herpesvirus
8 replication (70) which drove HCMV to evolve specific antagonists (71). Therefore, one
9 explanation for the blockade of STAT3 signal transduction might be interference with the
10 induction of antiviral proteins like PML.

11 But why should MCMV retain STAT3 phosphorylation? MCMV infection leads to
12 dramatically increased IL-6 secretion (72) and it has been shown that in absence of STAT3,
13 IL-6 induces STAT1 activation and initiates IFN γ -like responses (73). Thus, it is tempting to
14 speculate that MCMV invented this elaborated interference with STAT3 signalling (instead of
15 e.g. STAT3 degradation) to avoid that IL-6 in turn induces an IFN γ -like antiviral program.

16 Even though phosphorylated STAT3 is transcriptionally inert in terms of canonical STAT3
17 signal transduction and fails to induce classic target genes (e.g. SOCS3), it might nevertheless
18 fulfil other pro-viral functions in MCMV-infected cells. In this respect, it is noteworthy that
19 the HCMV-encoded IE1-pp72 utilizes phosphorylated STAT1 to elicit an IFN-like host cell
20 response (51) and that the HCMV major IE promoter (MIEP) contains IFN-responsive
21 promoter elements (called VRS1) which resemble STAT-binding sites (or GAS elements)
22 (74). It remains to be elucidated whether phosphorylated STAT3 binds to the MCMV genome
23 to modulate viral gene expression.

25 *Implications for the interpretation of CMV-induced and CMV-expressed cytokines*

26 CMVs induce cellular interleukins like IL-6 and IL-10 whereas HCMV even encodes
27 different splice isoforms of a viral IL-10 homolog. IL-6 and IL-10 signal via STAT3,
28 therefore an inhibition of STAT3-dependent signal transduction has considerable implications
29 for the interpretation of viral cytokine induction. Our results show that cells (e.g. fibroblasts)
30 which are productively infected by MCMV do not respond with a canonical STAT1/3
31 signalling. Therefore, secretion of STAT3-activating cytokines induced by CMV either have
32 to bypass the described inhibition or the cytokines exclusively act in a paracrine manner to
33 manipulate uninfected bystander cells. This interpretation is consistent with findings showing
34 that conditioned media derived from MCMV-infected cells induced MHC class II down

1 regulation upon transfer to uninfected cells in an IL-10-dependent manner (14). Additionally,
2 the expression of the viral STAT3 antagonists will most likely occur delayed in less
3 permissive cells (e.g. macrophages) so that STAT3-dependent signalling of cytokines like IL-
4 10 is preserved longer to execute the observed autocrine MHC II down modulation.

6 *An additional MCMV-encoded IFN antagonist*

7 Besides the implications for the understanding of phosphorylated STAT molecules and their
8 feedback regulation, our data reveal the existence of a yet unknown IFN antagonist encoded
9 by MCMV in addition to pM27. This inhibitor targets STAT1/3-dependent gene expression
10 on the transcriptional level without disturbing STAT1/3 phosphorylation. Our future work
11 will be focused on the elucidation of the identity of this particular viral inhibitor.

12 Since STAT1 and STAT3 fail to execute their transcriptional program despite their tyrosine
13 phosphorylation, the identity of the cellular interaction partner(s) of such an inhibitor might
14 be relevant for an understanding of STAT-induced transcription.

15 Taken together, our findings reveal the existence of a novel MCMV-encoded inhibitor of
16 JAK-STAT signalling which acts downstream of effected phosphorylation, but precludes
17 respective gene expression. This inhibition has the paradoxical consequence that
18 phosphorylation (normally a hallmark of activation) of STAT1 is prolonged and STAT3
19 phosphorylation is even ‘autonomously’ induced, due to blockade of the negative feedback
20 regulation.

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3 MT, VTKL and HH designed research. MT, VTKL, JRA, and BK performed research. VP,

4 GEA, SJ, JS, SRJ and KP provided crucial reagents. MT, VTKL and HH analyzed the data.

5 MT, VTKL and HH wrote the paper.

6

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Footnotes:

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Abbreviations used:

Foetal bovine serum, FBS; Gamma activated factor, GAF; gamma activated sequence, GAS; human CMV, HCMV; IFN-stimulated gene factor 3, ISGF3; IFN-stimulated response elements, ISRE; immediate early, *IE*; mouse cytomegalovirus, MCMV; suppressor of cytokine signalling, SOCS; transactivation domain, TAD, tyrosine kinase 2, Tyk2

Figure legends:

Fig. 1: MCMV abrogates STAT1 signalling after effected STAT1 Y701 phosphorylation, nuclear localization and DNA-binding

(A) Cells were infected with MCMV or left uninfected. 1 d post infection (d p. i.) cells were incubated for 30 min with mouse IFN γ (500 U/ml) and fractionated protein lysates (cytoplasm versus nucleoplasm) were prepared, normalized and subjected to SDS polyacrylamid gel electrophoresis (PAGE). The gel was blotted and the indicated proteins were detected by immunoblotting with indicated antibodies. (B) Nuclear translocation of STAT1 was tested as described in the M&M section (C) Native protein lysates of uninfected, wt-MCMV- or Δ M27-infected cells treated with IFN α , IFN γ or left untreated were subjected to EMSA analysis using a GAS probe as described in the M&M section. The identity of STAT1-containing complexes (indicated as 'GAF') was ensured by a super-shift upon addition of a STAT1-specific antibody to a lysate of IFN γ -conditioned cells (compare lanes 1 and 4). (D) Cells were either mock- or MCMV-infected (for 24 h with 10 PFU/cell) and subsequently exposed to 100 U/ml IFN γ for 30 min. Cells were lysed and subjected to ChIP analysis as described in the M&M section. (E) A clonal NIH3T3-based cell line harbouring a luciferase reporter gene under the control of a GAS promoter/enhancer element was generated. Cells were infected (10 PFU/cell) with the indicated viruses for 24 h and then IFN stimulated (100 U/ml) for 5 h. Afterwards, luciferase activity was quantified as described in the M&M section. Arithmetic mean and standard deviation are depicted. Statistical significance was tested using *t*-test (unpaired, two-sided) compared to the respective mock samples. (F) IFN γ -dependent (500 U/ml; 2 h) induction of *IRF-1* mRNA in uninfected and MCMV-infected (4+2 h p. i.; 10 PFU/ml) cells was tested by northern blotting.

Fig. 2: MCMV gene expression is required to induce IFNAR1-independent STAT3 phosphorylation

(A) Lysates of M2-10B4 cells infected with wt-MCMV (24 h p. i.; 10 PFU/cell) or left uninfected were subjected to immunoblot analysis detecting the indicated proteins. For a comparison, cells were incubated for 30 min with 20 ng/ml Hyper-IL-6. (B) As in (A) but M2-10B4 cells were compared with STAT3-deficient cells. (C) mHTC-K2 were infected with wt-MCMV or left uninfected. Protein lysates were analyzed by immunoblotting. In contrast to previous experiments, separate membranes were probed individually with the indicated antibodies and not sequentially using the same membrane. (D) NIH3T3 cells were infected with MCMV (10 PFU/cell). At indicated time points post infection, cells were lysed and

analysed by immuno blotting using STAT3- (left panel) and phospho-STAT3-specific antibodies (right panel). Four independent lysates were quantified. Shown is the relative abundance compared to mock cells. The mean values are depicted as dotted line. (E) As indicated, NIH3T3 cells were infected with grading infectious doses of wt-MCMV and analyzed by immunoblotting. (F) NIH3T3 and IFNAR1-deficient cells were stimulated for 30 min with 500 U/ml IFN α and STAT3 phosphorylation was tested by immunoblotting. (G) To describe the time course of viral STAT3 modulation, uninfected and wt-MCMV infected (10 PFU/cell) cells (IFNAR1-deficient and identically immortalized C57BL/6 fibroblasts) were lysed at indicated times [h] p. i. and probed for phospho-Y705-STAT3 and overall STAT3 amounts. (H) The necessity of viral gene expression for STAT3 modulation was tested by irradiating MCMV with grading UV doses (in J/m²) prior to ‘infection’. 24 h p. i. cells were lysed and subjected to immunoblotting. (I) The dispensability of cytomegaloviral *late* gene expression was analyzed by ganciclovir (GCV) treatment which inhibits genome replication and thereby largely reduces accompanying *late* gene expression.

Fig. 3: The MCMV-induced STAT3 phosphorylation is restricted to infected cells and not influenced by IL-6, IL-10 or JAK2

(A) NIH3T3, IL-6-, IL-10- and JAK2-deficient cells were tested for their capacity to support the MCMV-induced STAT3 modulation. Cells were infected (10 PFU/cell, 24 h p. i.) and subjected to immunoblotting using indicated antibodies. (B) In a medium transfer experiment, conditioned media of MCMV infected cells (which exhibit pronounced STAT3 Y705 phosphorylation) was inactivated (either by sterile filtration [‘sterile’] or by UV irradiation [‘UV’]) and subsequently transferred to uninfected NIH3T3 or RAW cells. STAT3 phosphorylation was assessed by immunoblotting. (C) In a transwell experiment (0.4 μ m membrane pore size), MCMV-infected and mock-infected cells were co-incubated sharing the same media. Cells were lysed separately and analyzed by immunoblotting. (D) wt-MCMV infected cells (10 PFU/ml; 24 h p. i.) and uninfected cells were cultured during the infection cycle with grading concentrations of foetal bovine serum (0 – 20% [v/v]). Cells were lysed and assessed by immunoblotting using the indicated antibodies. MCMV infection was visualized using a polyclonal anti-MCMV mouse immune serum (‘ α -MCMV’). One virus-specific band is depicted. Please note, that the viral gene expression was to a certain extend increased in cells being treated with higher FCS concentrations (data not shown).

Fig. 4: MCMV interferes with STAT3-dependent gene expression

(A) Fractionated protein lysates (cytoplasmic versus nucleoplasmic) of uninfected or wt-MCMV infected cells (10 PFU/ml, 24 h p. i.) treated for 1 h with or without 20 ng/ml Hyper-IL-6 were subjected to immunoblot analysis using the indicated antibodies. STAT3 target gene expression was analyzed by assessing SOCS3 amounts. (B) Northern blot analysis reveals the inhibition of Hyper-IL-6- (1 h; 20 ng/ml) and/or IFN γ (1 h; 500U/ml) -dependent mRNA induction of *SOCS3*, *SOCS1*, *IRF-1*, *JunB*, *cEBPD δ* , *STAT3* and *c-Myc* in cell infected with wt-MCMV (24+1 h p. i.). Appropriate RNA loading of the blotted gel was ensured by ethidium bromide staining of ribosomal 18S and 28S RNAs ('rRNA') and MCMV infection was documented by using an *ie1*-specific DNA-probe for hybridization.

Fig. 5: MCMV infection impairs Ser 727 phosphorylation of STAT3

NIH3T3 cells were infected with 10 PFU/cell wt-MCMV, Δ M27-MCMV, UV-irradiated (10,000 J/m²) wt-MCMV or left uninfected. 24 h p. i. cells were either treated with 20 ng/ml Hyper-IL-6, 500 U/ml IFN γ or left untreated for 15 min. Cells were lysed and subjected to immunoblot using the indicated antibodies.

Fig. 6: MCMV infection prolongs STAT1 phosphorylation

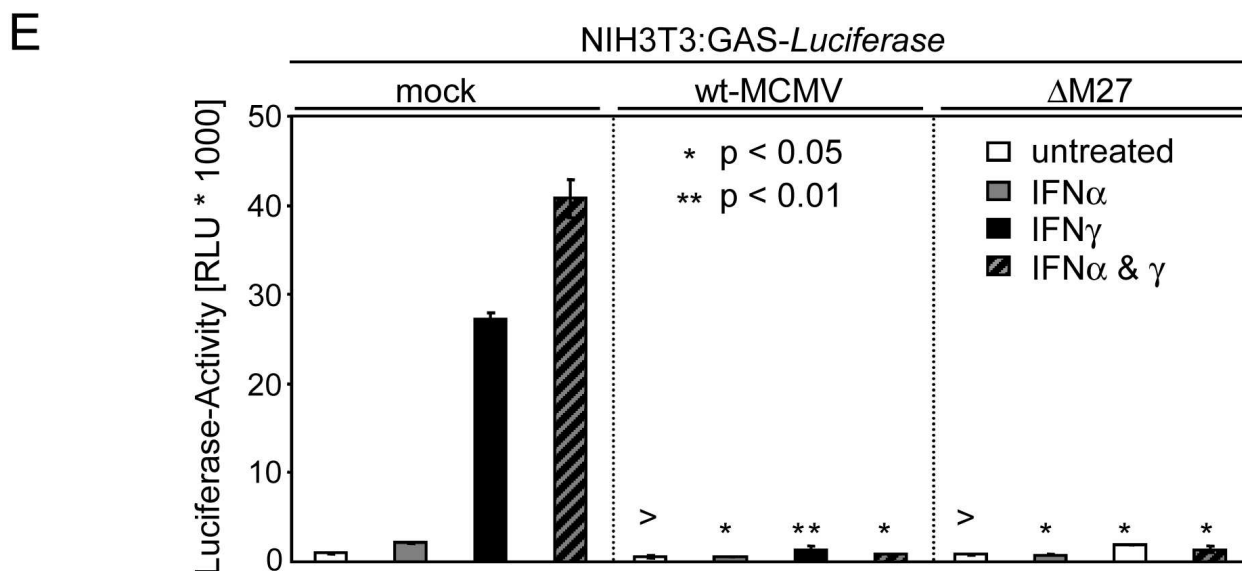
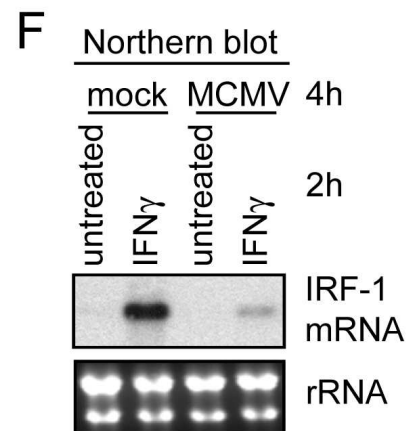
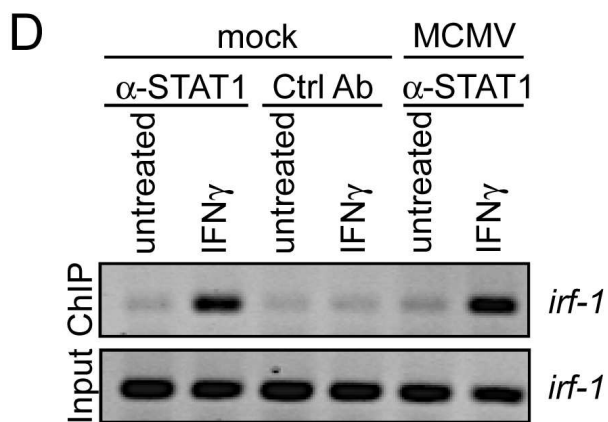
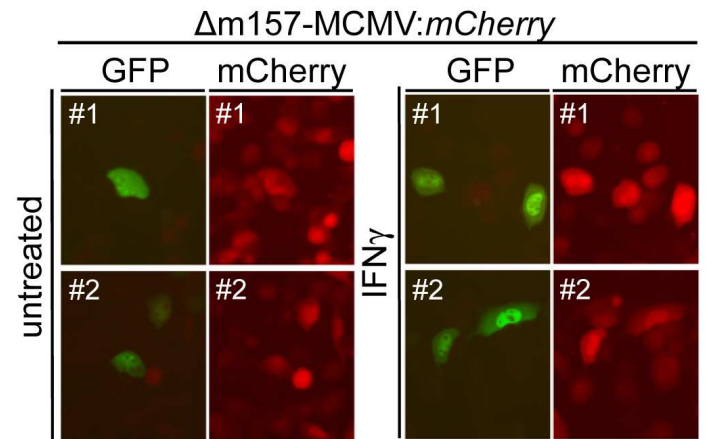
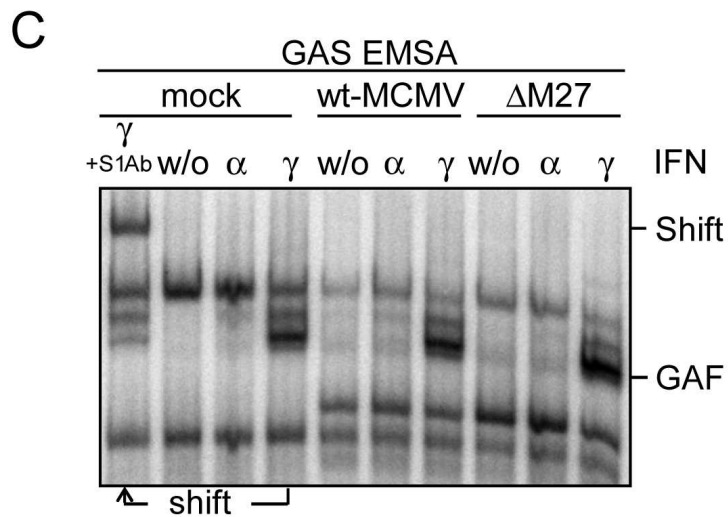
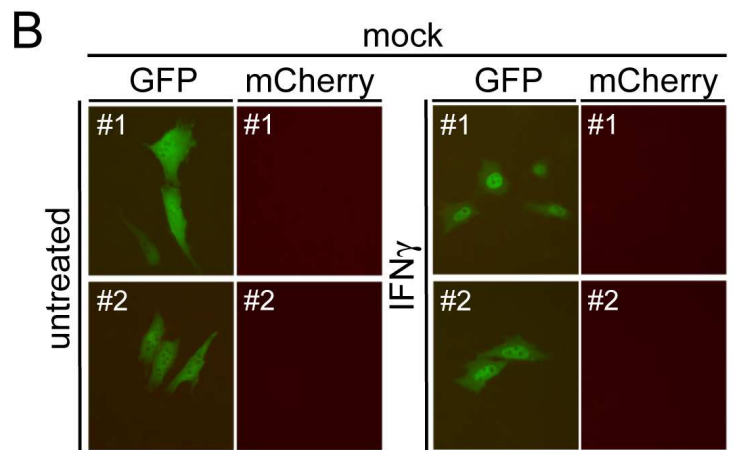
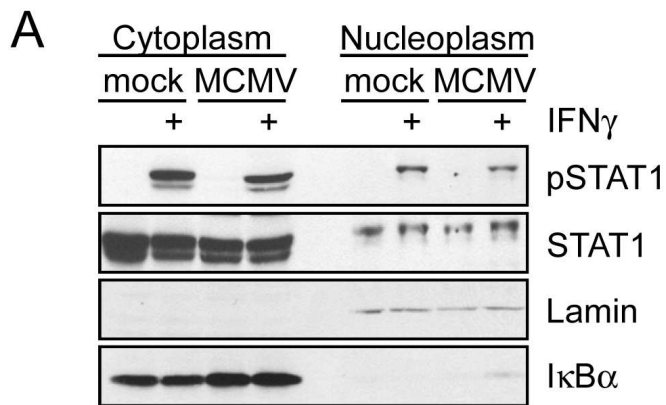
NIH3T3 cells were infected with wt-MCMV or Δ M27-MCMV or left uninfected (24 h p. i.; 5 PFU/ml) and subsequently pulsed with IFN γ (500 U/ml; 30 min). Afterwards, IFN γ was removed by vigorously washing the cells and protein lysates were prepared at the indicated time points post washing procedure ('chase' time in min) to follow the kinetic of STAT1 phosphorylation and dephosphorylation. The indicated proteins were detected by immunoblotting.

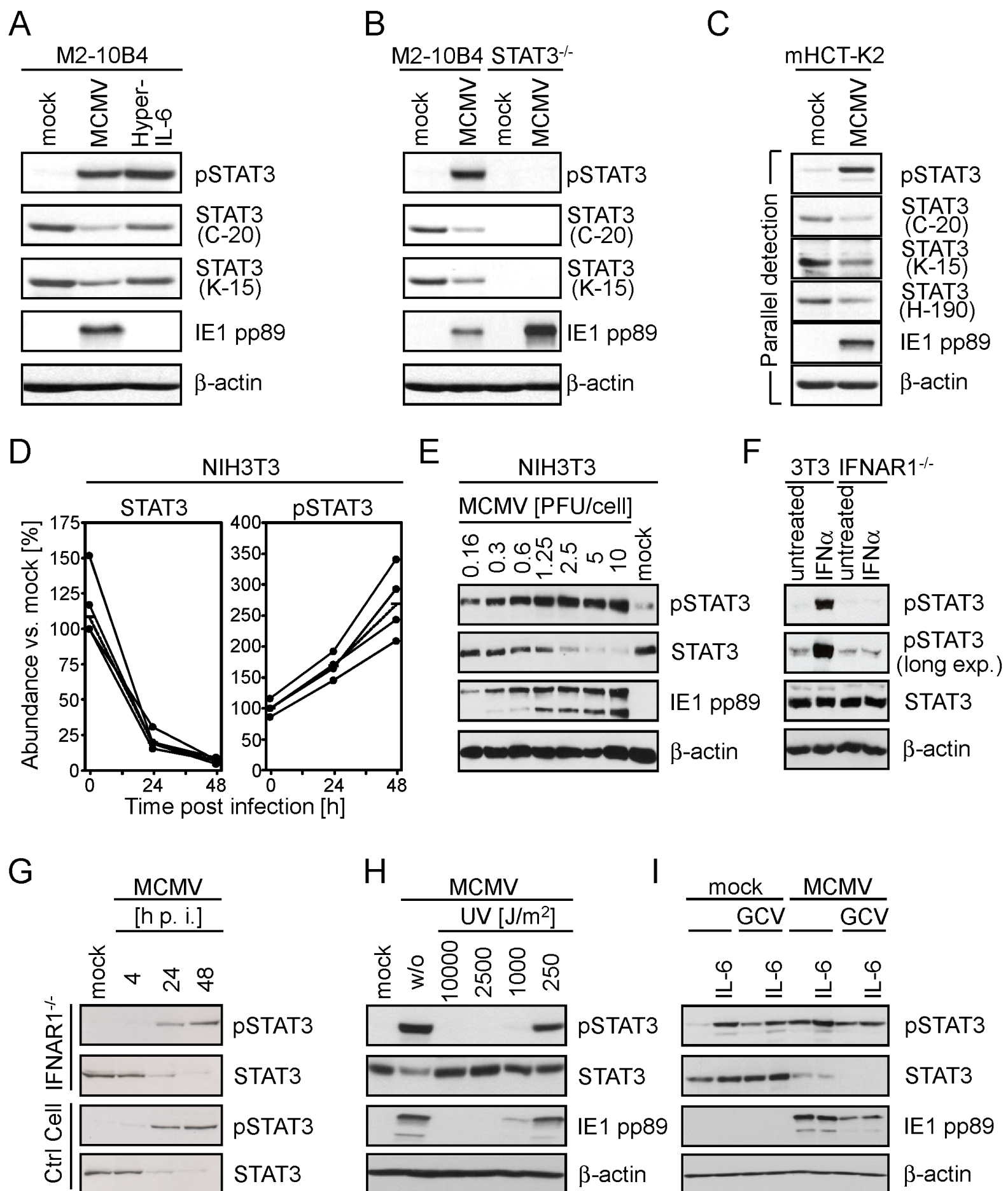
Fig. 7: Neither pIE1 nor pM27 are essential for the cytomegaloviral STAT3 regulation.

(A) NIH3T3 cells were infected (10 PFU/ml; 24 h p. i.) with an *IE1*-deletion MCMV, the respective parental virus ('wt') or left uninfected. Cells treated by Hyper-IL-6 (1 h; 20 ng/ml) or left untreated. Mixtures of nuclear and cytoplasmatic fractions (1/1 ratio) were subjected to immunoblot analysis. The deficiency for *IE1* was documented by probing pIE1-pp89 and comparable infection was ensured by probing the viral protein pM45. (B) As in (A), but wt-MCMV and Δ M27-MCMV were compared.

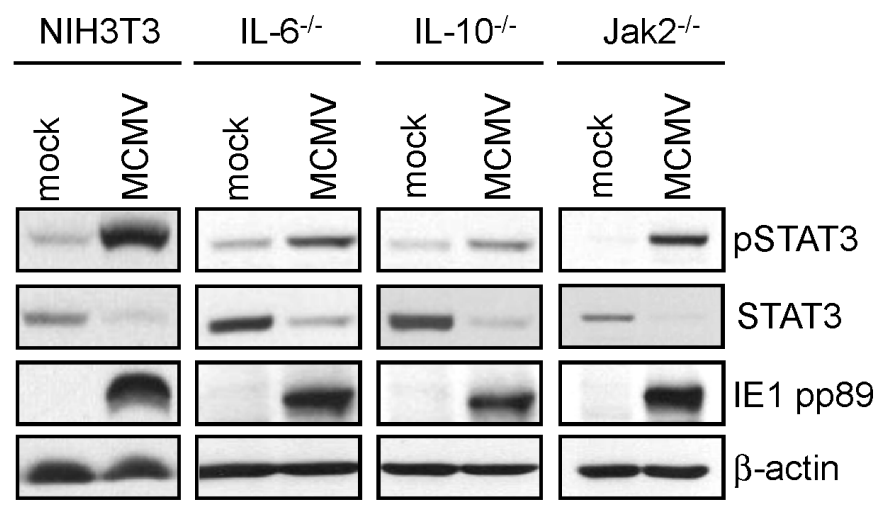
Fig. 8: MCMV reveals a dynamic equilibrium of STAT3 activation and inactivation.

1 **(A)** The supposed dynamic equilibrium of STAT3 phosphorylation, expression of mediators
2 of the negative feed-back loop (e.g. SCOS3) and STAT3 dephosphorylation in MCMV
3 permissive cells (NIH3T3) was tested by incubation of cells with the broad spectrum
4 phosphatase inhibitor sodium vanadate (Na_3VO_4 ; 100 μM) for the indicated time periods.
5 Cells were lysed and subjected to immunoblot analysis. **(B)** as in (A) but MCMV-infected and
6 uninfected cells were treated with 10 and 100 μM sodium vanadate, respectively, starting at
7 the time of infection or one day post infection.

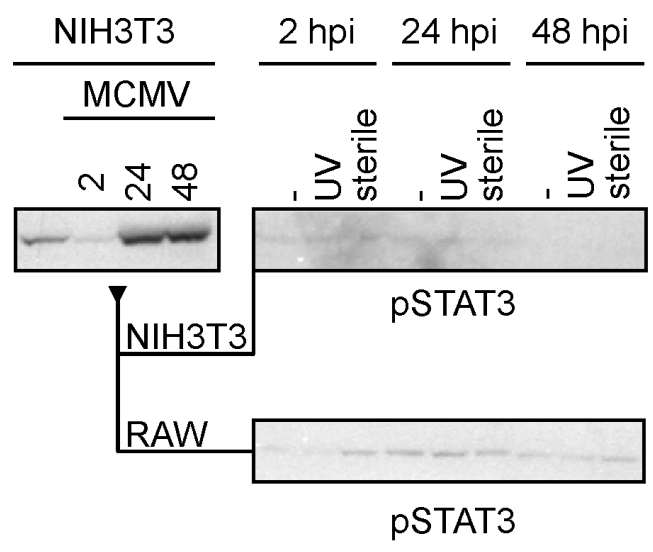




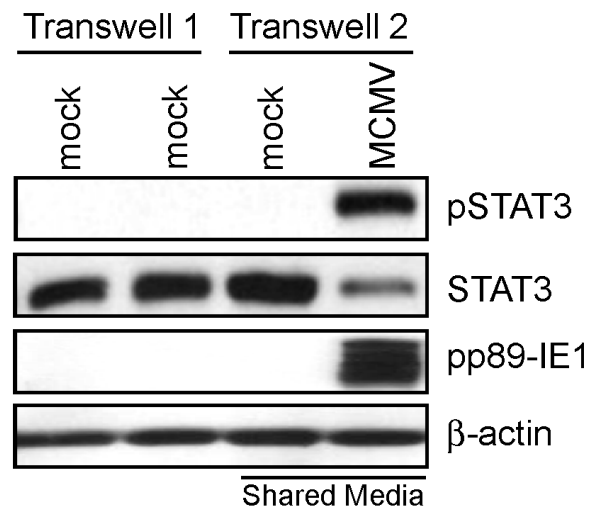
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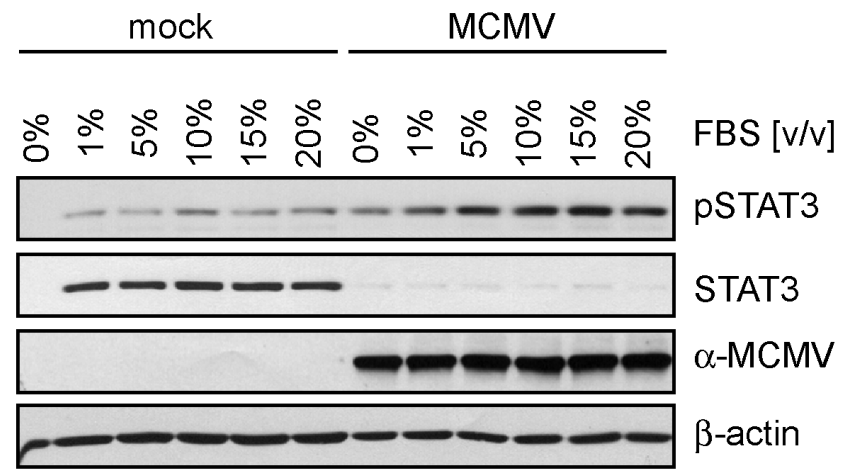
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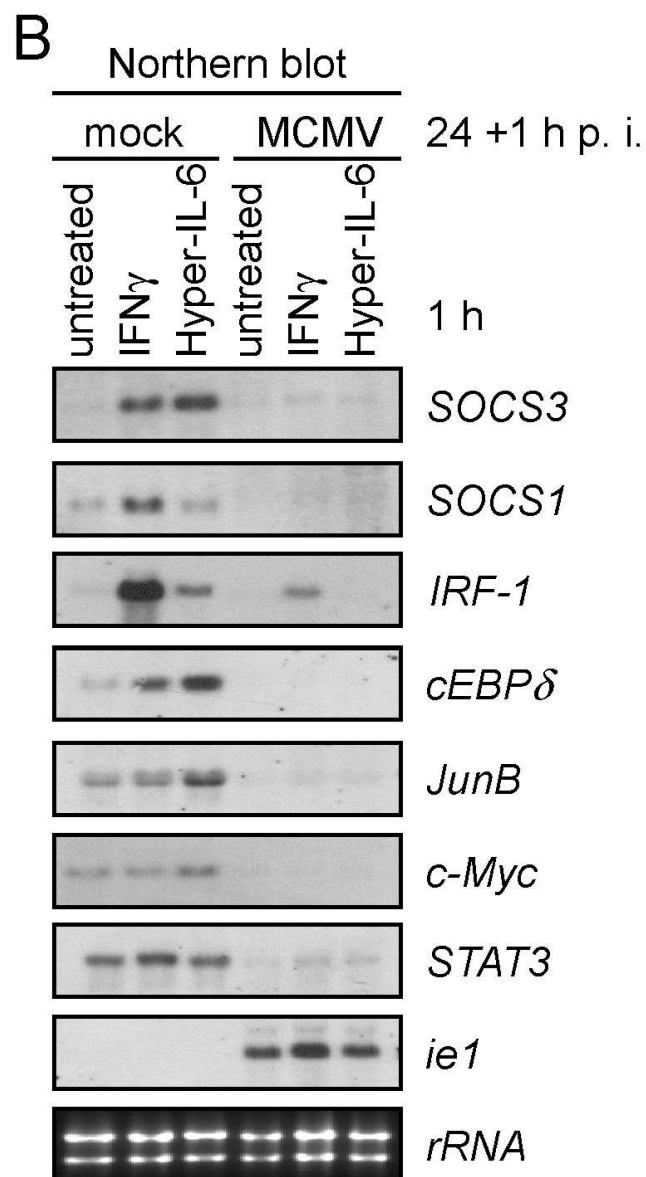
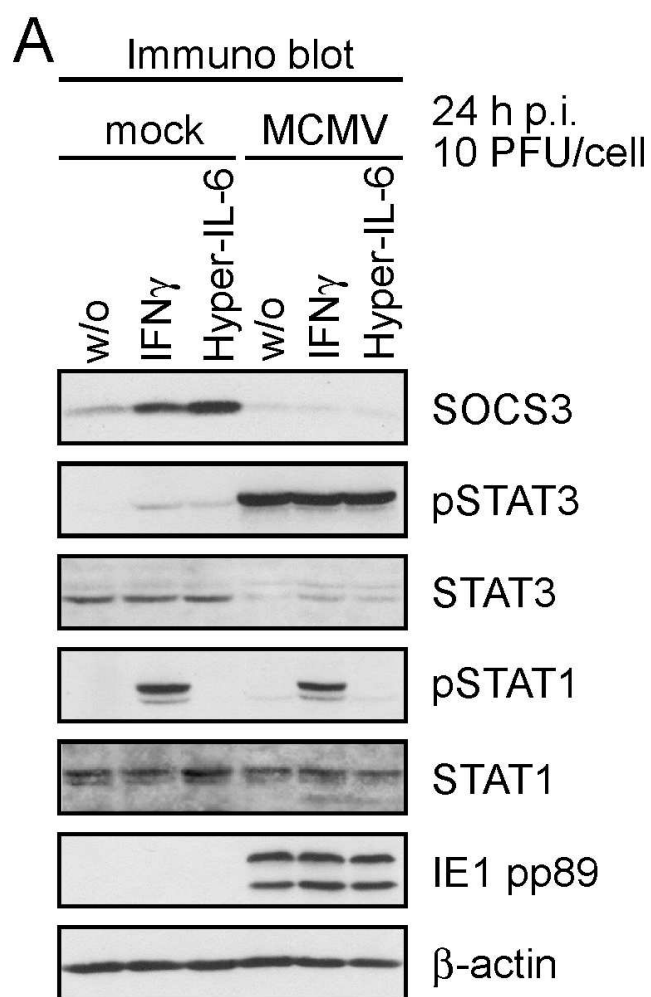


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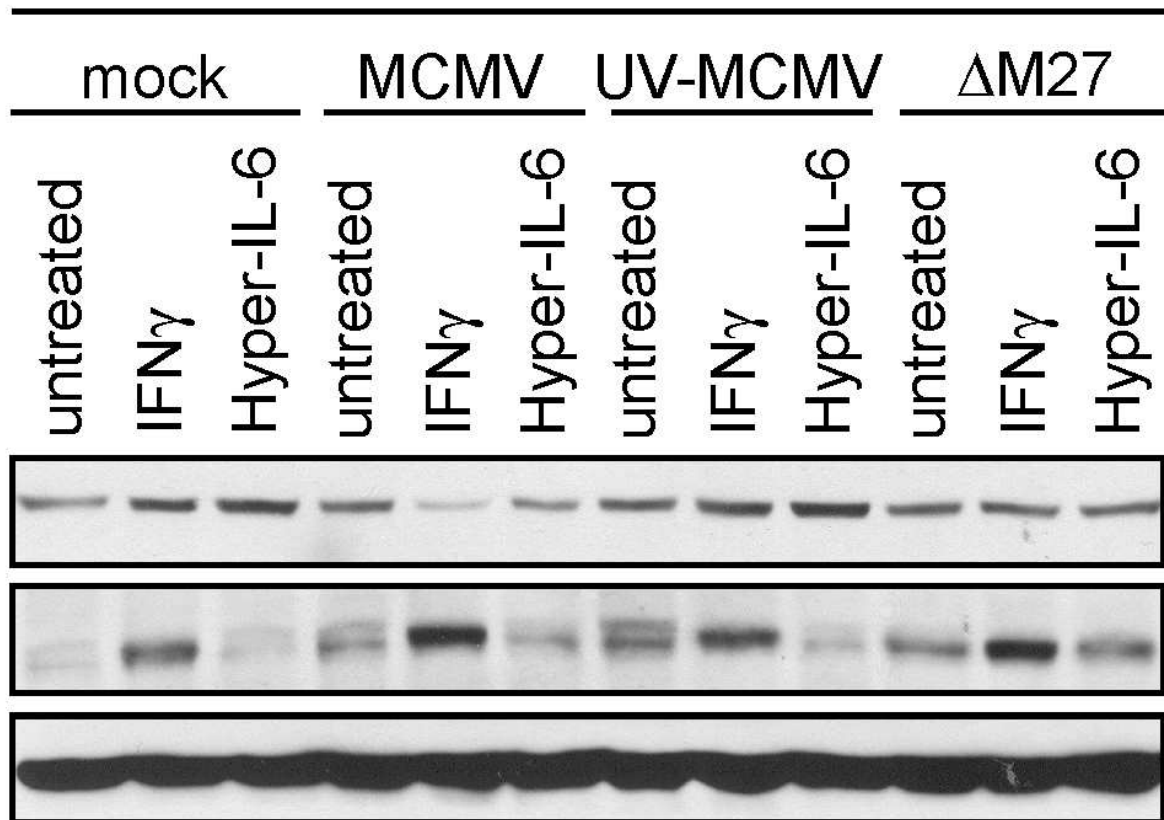
D





WB: NIH3T3

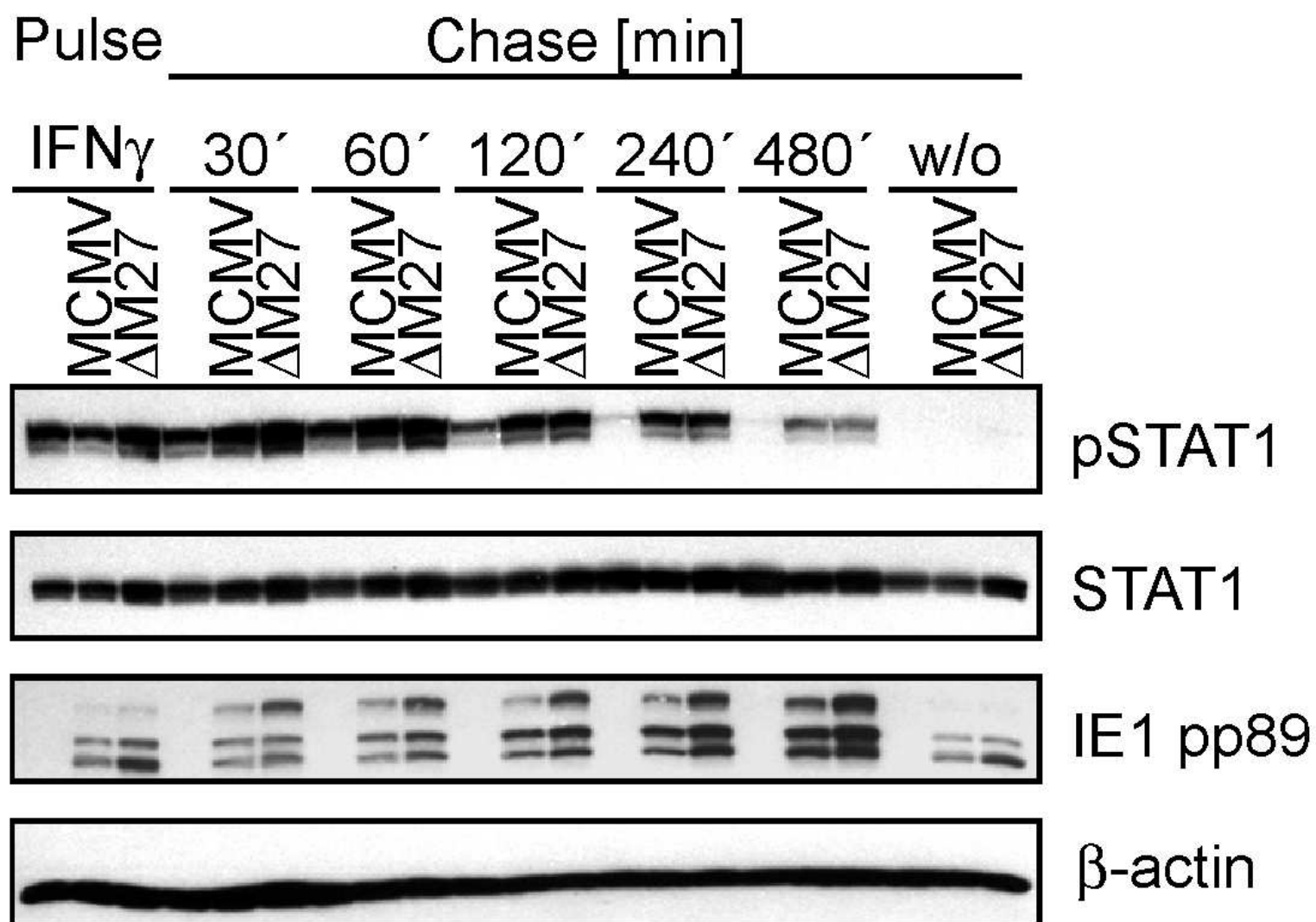
24 h p.i.
10 PFU/cell



pSer-STAT3

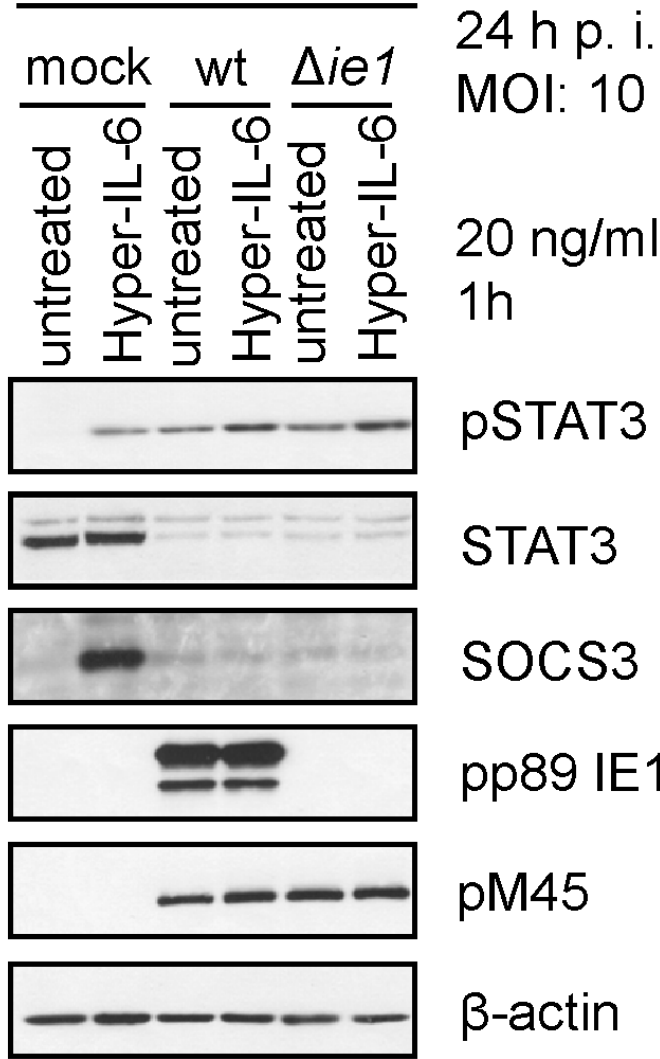
pSer-STAT1

β -actin



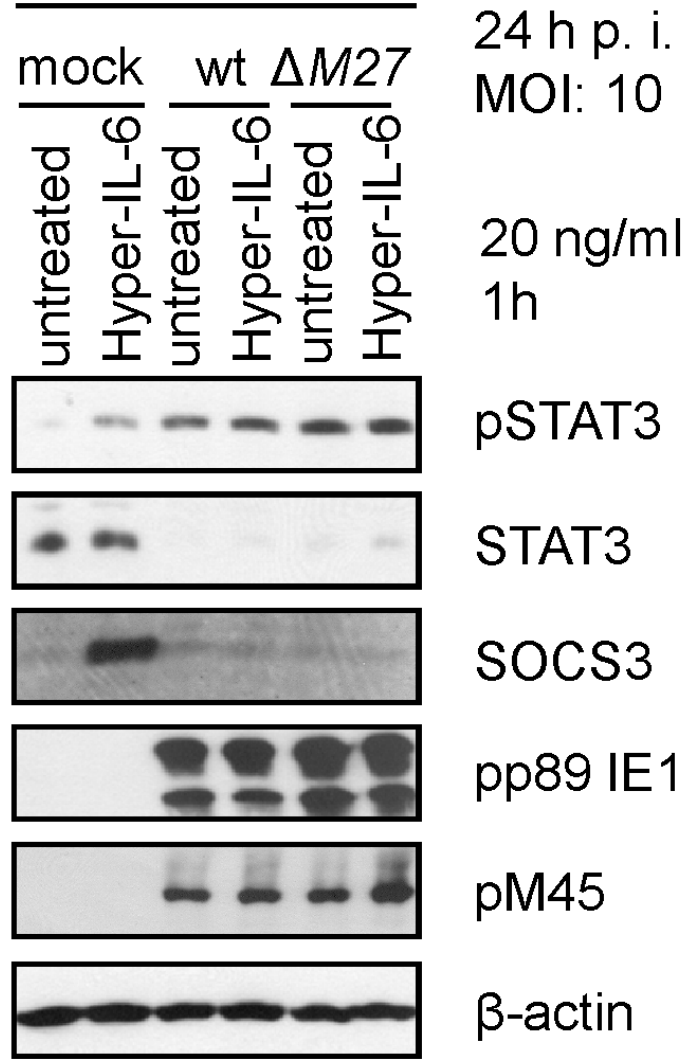
A

NIH3T3

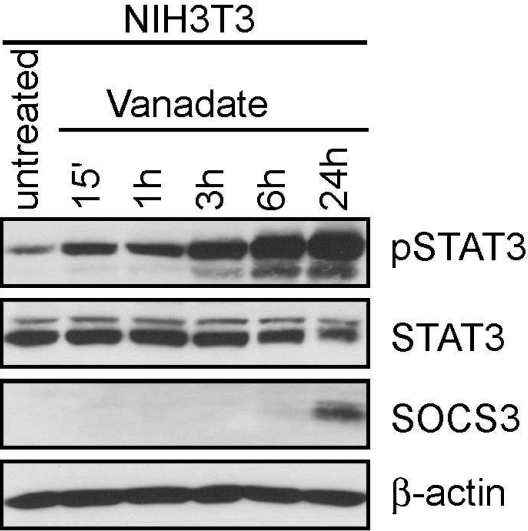


B

NIH3T3



A



B

